Computer Simulations of VANETs Using Realistic City Topologies

Francisco J. Martinez, Manuel Fogue
University of Zaragoza, Spain
Email: {f.martinez, m.fogue}@unizar.es
C. K. Toh
National Tsing Hua University, Taiwan
Email: ck_away@hotmail.com
Juan-Carlos Cano, Carlos T. Calafate, Pietro Manzoni
Universitat Politècnica de València, Spain
Email: {jucano, calafate, pmanzoni}@disca.upv.es

Abstract

Researchers in Vehicular Ad Hoc Networks (VANETs) commonly use simulation to test new algorithms and techniques. This is the case because of the high cost and labor involved in deploying and testing vehicles in real outdoor scenarios. However, when determining the factors that should be taken into account in these simulations, some factors such as realistic road topologies and presence of obstacles are rarely addressed. In this paper, we first evaluate the packet error rate (PER) through actual measurements in an outdoor road scenario, and deduce a close model of the PER for VANETs. Secondly, we introduce a topology-based visibility scheme such that road dimension and geometry can be accounted for, in addition to LOS (line-of-sight). We then combine these factors to determine when warning messages (i.e., messages that warn drivers of danger and hazards) are successfully received in a VANET. Through extensive simulations using different road topologies, city maps, and visibility schemes, we show these factors can impact warning message dissemination time and packet delivery rate.

Index Terms

Vehicular ad hoc networks; attenuation and visibility schemes; VANET simulation; city maps.

I. Introduction

Vehicular ad hoc networks (VANETs) are wireless communication networks that do not require any sort of fixed infrastructure, offering a novel networking paradigm to support cooperative driving applications on the road. VANETs are characterized by: (a) constrained but highly variable network topology, (b) specific speed patterns, (c) time and space varying communication conditions (e.g., signal transmissions can be blocked by buildings), (d) road-constrained mobility patterns, and (e) no significant power constraints.

Deploying and testing VANETs involves high cost and manpower. Hence, simulation is a useful methodology tool prior to actual implementation [1]. Simulations of VANETs often involve large and heterogeneous scenarios. One of the important issues when creating a simulation environment in VANETs is to correctly model how vehicles move. Based on a study about the mobility behavior of mobile users [2], existing models try to closely represent movement patterns. These models provide a suitable environment for the simulation and evaluation of ad hoc communications performance.

IEEE 802.11p [3] is an amendment to the IEEE 802.11 standard to add *Wireless Access in the Vehicular Environment* (WAVE). It defines enhancements to 802.11 required to support *Intelligent Transportation Systems* (ITS) applications, including data exchange between moving vehicles and between vehicles and roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz).

In urban scenarios, and at the frequency of 5.9 GHz (i.e., the frequency band adopted by the 802.11p standard), radio signals are highly directional and will experience a very low depth of penetration [4], [5]. Hence, in most cases, buildings will absorb radio waves at this frequency, making most communications only possible when vehicles are in line-of-sight (LOS). In order to accurately simulate how radio signals propagate in urban scenarios, we must consider the effect of signal attenuation due to distance, along with the effect of obstacles blocking signal propagation. Therefore, to better simulate wireless signal propagation, both attenuation and visibility schemes should be taken into account.

When taking into account visibility schemes, the topology of the map used to constrain vehicle movement is very important. Using complex layouts implies more computational time, but the obtained results are expected to be closer to the real ones. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). Layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the obtained results are likely to be similar to those obtained in realistic environments. In this paper, we present our novel *Topology-based Visibility* model, which enables a more precise warning message propagation process, taking into account both attenuation and visibility in real urban scenarios [6]. We then validate our proposed model, evaluating the process of message dissemination in several real VANET scenarios to detect variations under different topologies.

The rest of the paper is organized as follows: Section II presents several existing signal attenuation and visibility schemes for VANETs and their limitations. In Section III we elaborate our Topology-based Visibility Model. Section IV presents the simulation environment which will be used to validate our model. Simulation results are described in Section V. Section VI provides an overall discussion of the proposed approach, and, finally, Section VII concludes this paper.

II. Warning Message Dissemination - Attenuation & Visibility Issues

Warning Message Dissemination is one of the key applications of VANETs. Its implications in traffic safety are very important, since many of the dangerous (or annoying) situations a vehicle can face could be drastically reduced or even avoided if drivers received enough information from nearby vehicles. Useful information for drivers include potential dangers (accidents, slippery roads, etc.) and delays (due to traffic jams, public works, etc.) detected by other vehicles. However, a key factor of this information is that it is totally useless if it is not delivered in time. For example, if a vehicle is notified about a traffic jam when it has indeed arrived at the affected area, the information is not useful at all.

Warning message dissemination using wireless technology in urban environments is affected by several factors, such as signal propagation and the presence of obstacles interfering with the wireless signal. Hence, dissemination schemes should be validated under conditions accounting for these effects. Many of the existing works make use of simplifications or they do not even include some of these factors, and so conclusions obtained using these approaches should be revised carefully.

A. Limitations of Existing Attenuation Schemes

An important effect experienced by a radio signal is its loss of power density as it propagates through a specific environment. To estimate the impact of signal attenuation on packet losses without extending simulation run-time, we relate the *Bit Error Rate* (BER) and *Packet Error Rate* (PER) to the distance between sender and receiver under specific channel conditions, calling these formulations *Attenuation Schemes*. Other existing factors which could affect the values of BER and PER (like the modulation type, the channel coding scheme, etc.) are not included as these factors remain constant in our simulations.

The ns-2 simulator [7], in version 2.33, offers some schemes to account for wireless signal strength, but none of them support obstacle modeling within the network. Two of them, the Free Space and the Two-ray Ground models, determine if a packet is received using a deterministic process, since only the power level is taken into account. Probabilistic models are also included, such as the Rayleigh and the Ricean fading models, the Nakagami model and the Shadowing model. However, they are based on probabilistic distributions that do not use information about the specific scenario, and hence line-of-sight (LOS) conditions are treated in the same way as non-line-of-sight (NLOS) situations.

In existing literature, we find several attenuation schemes that model the presence of obstacles. The most cited ones are:

- Radio Propagation Model with Obstacles [8]: It includes a simple obstacle model for synthetic Manhattan-grid scenarios, but distance attenuation is not taken into account.
- Mahajan et al. proposal [9]: This model adds the influence of obstacles and distance attenuation, but it has been designed specifically under the 802.11g technology, where radio signal absorption by buildings is different from 802.11p.

B. Limitations of Existing Visibility Schemes

As previously mentioned, one relevant effect affecting radio propagation (especially at the frequency of 5.9 GHz) is the signal absorption due to obstacles in the environment, i.e., buildings and geographic conditions such as mountains. In our simulations, we focus on urban scenarios, thus taking into account the low depth of penetration of the wireless signal into buildings and other urban artifacts. Simulation results will largely depend on how this effect is modeled.

The simplest approach concerning visibility is not to consider obstacles at all, as if vehicles were moving in an empty surface. This is the default model implemented within the ns-2 simulator. Its major drawback is that it will cause the obtained results to be little realistic, as it always considers that vehicles in urban scenarios are

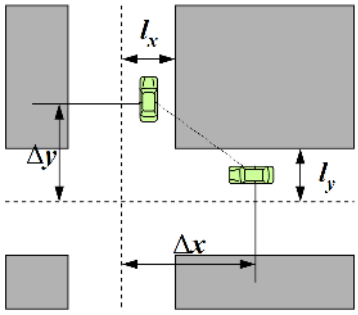


Fig. 1. Parameters to determine if two vehicles are in line-of-sight in a Manhattan layout.

in line-of-sight. A variation of this scheme is reducing the scenario to a simple highway where all the vehicles move in the same direction, like the ones found in [10] and [11].

A more complex scheme, used in [12] and [8], assumes that all vehicles are moving only in streets arranged in a Manhattan-style grid, so that vehicle movements can only be vertical or horizontal. This environment is more realistic than previous ones, but in real scenarios (e.g. many European cities) it is very difficult to find perfect Manhattan layouts. In a Manhattan-style visibility scheme, two vehicles in different streets are in line-of-sight when the following condition is satisfied (see Figure 1):

$$(\Delta x < l_x) \vee (\Delta y < l_y) \vee \left(\frac{-\Delta y \times l_x}{\Delta x} + \Delta y < l_y \right), \tag{1}$$

where Δx is the absolute difference between the x coordinates of the two vehicles ($\Delta x = |x_1 - x_2|$), Δy is the absolute difference between the y coordinates of the two vehicles ($\Delta y = |y_1 - y_2|$), l_x is the half of the streets' width in the x coordinate, and l_y is the half of the streets' width in the y coordinate.

This approach is simple and easy to implement in a simulator, and it provides information about the general trends of the different algorithms. However, a more realistic layout should be used to ensure that the obtained results are closer to reality. Visibility is mainly affected by (a) obstacles such as buildings, and (b) road topologies. This means that the propagation process will have a very different efficiency depending on the layout of the scenarios, since maps with many irregular streets slow down the dissemination process as it is less likely to find vehicles in line-of-sight. On the contrary, Manhattan-like topologies allow messages to reach longer distances through their long straight streets, making easier to contact a high percentage of vehicles.

Synthetic Manhattan-grid scenarios, although simple, tend to be excessively optimistic. This is the reason why our proposal includes a new visibility modeling scheme (see Section III-B) which can be used with any real roadmap constructed as a street graph.

III. Our Model of Warning Message Dissemination

As shown in Sections II-A and II-B, a wireless signal propagation model can be characterized by: (a) attenuation, and (b) visibility schemes. The combination of these two characteristics makes up our novel warning message dissemination model for VANETs, called *Topology-based Visibility* model.

To determine if a packet is successfully received using our proposed model, each packet needs to pass both the attenuation and the visibility tests before it can be considered correctly transmitted. Below, we further elaborate on both the attenuation and the visibility schemes our approach uses.

A. Attenuation Scheme

Our model implements signal attenuation (due to the distance between vehicles) as closely as possible to reality. In general, ns-2 offers deterministic attenuation schemes, i. e., the selected function determines the maximum distance a packet could reach. If the receiver is within this range, the packet will be successfully received; on the contrary, if the distance is greater, it will be lost. In order to increase realism, we use a probabilistic approach to this problem to model packet losses due to collisions or other situations. So, we use a probability density function to determine the probability of a packet being successfully received at any given distance.

Our scheme is based on real data obtained from experiments in the 5.9 GHz frequency band using the IEEE 802.11a standard, which uses the same band as 802.11p[1]. The experiments consisted of several measurements of the *Packet Error Rate* (PER) under varying distance between sender and receiver (from zero up to 500 meters), and different packet sizes (from 32B to 1024B). For every combination of distance and packet size, 10 series of 1,000 UDP packets were sent using broadcast in different time periods (to avoid time-specific environmental interference) between sender and receiver and the PER was estimated as a quotient between the number of unsuccessfully received packets and the total number of packets sent. In these experiments, we obtained an empirical maximum transmission range of 400 meters. Figure 2 shows the map of the physical location where the experiments took place.

Using the collected data, we tested several monotonically increasing functions for the curve fitting process and found that an acceptable trade-off between accuracy and execution time could be achieved using a fourth order polynomial:

$$PER(x) = \left\{ \begin{array}{ccc} 0 & \text{if} & x < 320\,m. \\ ax^4 + bx^3 + cx^2 + dx + e & \text{if} & 320\,m. \leq x < 400\,m. \\ 1 & \text{if} & x \geq 400\,m. \end{array} \right\} \qquad (2)$$

where PER is the Packet Error Rate and x is the Euclidean distance between vehicles. In particular, the values obtained through regression were:

(a, b, c, d, e) = (5.29e–10, –3.37e–7, 6.61e–5, –0.004, 0.03)

To measure the goodness of our curve fitting process we calculated the reduced chi-square, obtaining a value of 0.0046 which shows that our model fits well with the experimental results.

With respect to other attenuation schemes, such as Two-Ray Ground and Nakagami, our scheme is obtained directly from experimental data. Moreover, instead of using a deterministic approach, we use a probabilistic

[1]Tests with the IEEE 802.11p standard were infeasible because of the lack of devices implementing this technology.

Fig. 2. Aerial snapshot of the location where PER measurements were made using 802.11a (from Google Maps).

function to model packet losses. Our function determines the probability of successful reception depending on the distance between sender and receiver. Hence, to determine if a transmission passes the attenuation scheme, a random number between 0 and 1 is obtained from a uniform distribution. If it is higher than the probability determined by the function, the attenuation test succeeds.

Figure 3 shows the empirical data obtained in our experiments and our proposed attenuation curve model compared with: (a) Two-Ray Ground, (b) Nakagami [13], and (c) the *Building and Distance Attenuation Model* (BDAM) [14]. As can be seen, the only deterministic scheme is the Two-Ray Ground model, which is represented with a maximum transmission range of 250 meters (as used by most authors). The Nakagami scheme has a slightly greater range, but the probability of successful transmission when the distance is above 200 meters is too low. The BDAM attenuation scheme behaves similarly to our scheme, but for distances above 300 meters the probability of successfully transmitting is much higher using our attenuation scheme.

B. Visibility Scheme

In most cases, when using the 5.9 GHz frequency band (used by the 802.11p standard), buildings absorb radio waves and so communication is not possible. The main objective of our realistic visibility scheme is to determine if there are obstacles between the sender and receiver which will interfere with the radio signal. A previous model called *Building and Distance Attenuation Model* (BDAM) [14] was proposed to work only in Manhattan-style grid layouts, where simpler calculations were used to determine if two vehicles were in line-of-sight. Figure 4 depicts the BDAM model, where dark rectangles represent buildings.

Our proposal goes one step further by adapting the algorithm to support more complex and realistic street

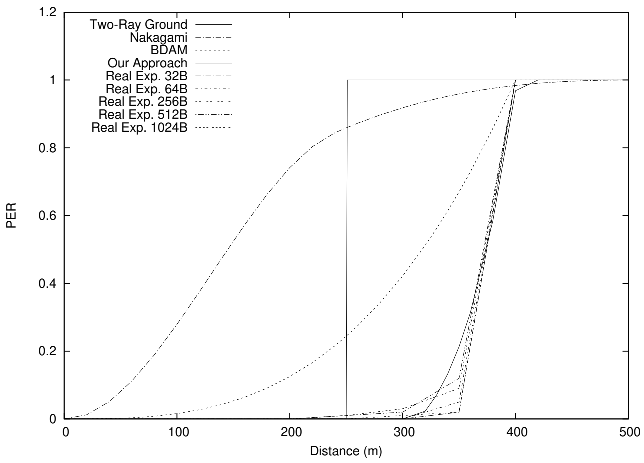


Fig. 3. Comparison of different attenuation schemes with respect to the obtained experimental data (varying packet size from 32 bytes to 1024 bytes). The curve of our approach fits the empirical data for packets of 256 bytes.

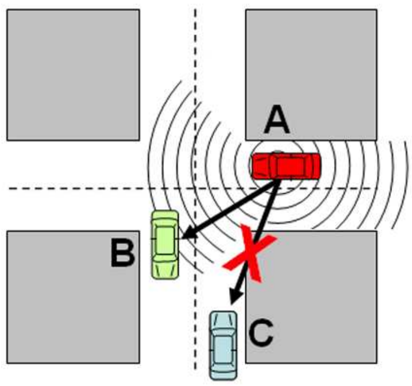


Fig. 4. BDAM visibility scheme: an example scenario.

layouts, since it takes into account realistic road topologies, such as roundabouts, angled roads, merged-and-split roads, etc., that are not considered by other schemes. Given a real reference map containing the street layout, the roadmap is converted into an undirected graph where junctions are vertices and streets are edges that connect some pairs of vertices. We use a notation to define streets in which (x_s^1, y_s^1) is the initial vertex of the street s, and (x_s^2, y_s^2) represents its end vertex. Some of the polygons formed using the streets as sides are considered clear areas with little interference in the signal propagation (obstacle-free areas such as roundabouts, gardens, etc.), and the rest of map is regarded as a set of buildings which prevents signal from propagating, obtaining a realistic city profile.

Figure 5 shows an example of our visibility scheme, where vehicle (A) is trying to disseminate a message. In that case, and assuming that any vehicle receiving a message will rebroadcast it the first time, the result will be vehicles B, C, D, and E receiving the message while the others (F, G, H, and I) will not receive it. The visibility scheme considers that radio signal can be propagated through streets and clear areas whereas the

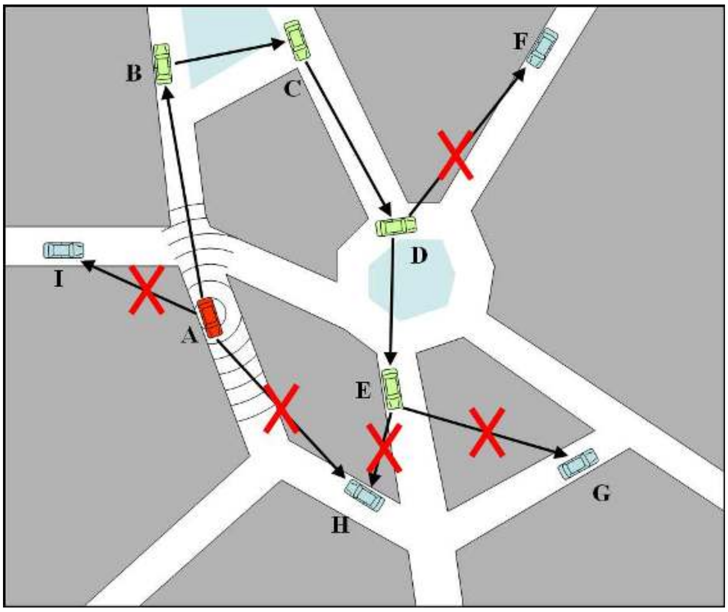


Fig. 5. Our visibility scheme: example scenario. Dark polygons represent buildings and light areas are clear spaces between streets.

signal is mostly inhibited from passing through solid buildings.

1) Vehicles in the same street: Since our roadmaps are constructed as graphs where streets are straight (curved streets are approximated as a series of straight streets), two vehicles in the same street are considered to be in line-of-sight since no buildings interfere with the signal path. Thereby, the first test consists of consulting the street file to obtain the current street for each vehicle, and then determine if two vehicles with possibility of communication are located in the same street. If this test is satisfied, then the visibility scheme is passed.

2) Vehicles in different streets: We now focus on determining when vehicles located in different streets are in line-of-sight. First of all, it is necessary to check if there is an open area between the two vehicles that allows communication. This can be obtained by storing the polygons formed as areas delimited by the edges of the graph, i.e., the streets. When two vehicles are trying to communicate, the polygons intersecting with the segment created using their positions as bounds are potentially able to interfere with the wireless signal. If all intersecting polygons are marked in the scenario as an open area, then the two vehicles are considered to be in line-of-sight and no additional tests are needed. As shown in Figure 6, the highlighted areas should be checked for obstacles before going on with the visibility test between vehicles A and B.

A polygon intersects with a line segment when any of its sides (viewed as segments too) intersects with the chosen segment. In fact, since the vehicles cannot be located inside one of these polygons, the number of intersecting sides will be at least two. Two segments intersect with each other when they have any point in common. Hence, if we have four 2D points, $A(a_1, a_2)$, $B(b_1, b_2)$, $C(c_1, c_2)$ and $D(d_1, d_2)$, forming segments $\bar{AB}$ and $\bar{CD}$, we can express the points belonging to these segments in terms of parameters t and s as:

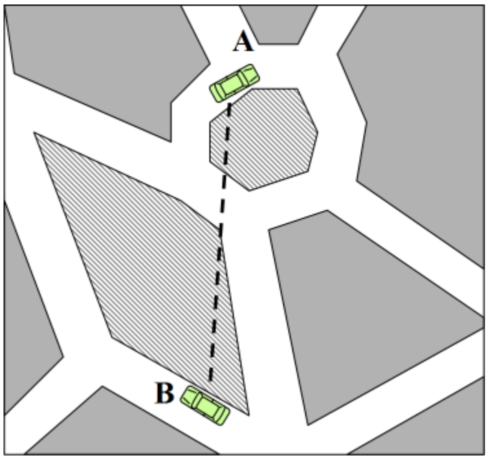


Fig. 6. City areas represented as polygons between two vehicles.

$$\vec{OP}(t) = \vec{OA} + t \cdot \vec{AB}$$
$$\vec{OQ}(s) = \vec{OC} + s \cdot \vec{CD} \tag{3}$$

Where $t \in [0, 1]$ and $s \in [0, 1]$. The intersecting point must be common to both segments, thus the following equality must be fulfilled:

$$\vec{OP}(t) = \vec{OQ}(s) \tag{4}$$

If we continue operating, we eventually obtain a system of linear equations.

$$\vec{OP}(t) = \vec{OQ}(s)$$

$$\vec{OA} + t \cdot \vec{AB} = \vec{OC} + s \cdot \vec{CD}$$

$$(a_1, a_2) + t \cdot (b_1 - a_1, b_2 - a_2) = (c_1, c_2) + s \cdot (d_1 - c_1, d_2 - c_2)$$

$$\begin{Bmatrix} a_1 + t \cdot (b_1 - a_1) = c_1 + s \cdot (d_1 - c_1) \\ a_2 + t \cdot (b_2 - a_2) = c_2 + s \cdot (d_2 - c_2) \end{Bmatrix} \tag{5}$$

Solving the system of equations to find t and s will determine if the two segments intersect. If $t \in [0, 1]$ and $s \in [0, 1]$, it will mean that the point is located inside both segments and they intersect, while another set of solutions (or no solution at all) will mean that there is no intersection point between them.

If any of the areas between the vehicles is a building, another additional test must be performed to ensure communication is possible. The values we must know *a priori* for this test are the coordinates of vehicle A (x_A, y_A), the coordinates of vehicle B (x_B, y_B), the angle (α) formed by the streets where the two vehicles are moving, and the coordinates of the vertex V (x_V, y_V) the two streets have in common. Figure 7 shows the

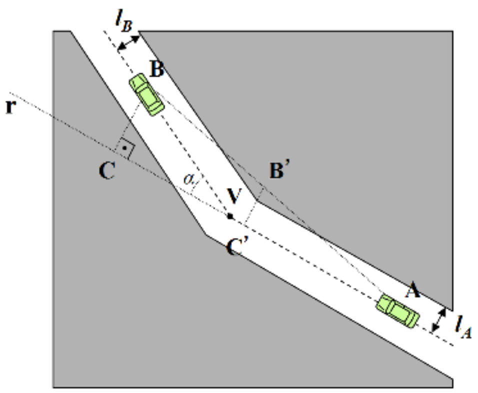


Fig. 7. Parameters to determine if two nodes are in line-of-sight in a realistic layout.

mathematical basis of the visibility model proposed for this situation. As we can see, vehicles A and B are in line-of-sight if the following condition is satisfied:

$$d(B', C') < l_A \tag{6}$$

Function d represents the Euclidean distance between two points, and l_A is half the width of the street where vehicle A is located. We can find the value of $d(B', C')$ as follows:

$$\frac{d(B,C)}{d(A,C)} = \frac{d(B',C')}{d(A,C')} \Rightarrow d(B',C') = \frac{d(A,C') \cdot d(B,C)}{d(A,C)} \tag{7}$$

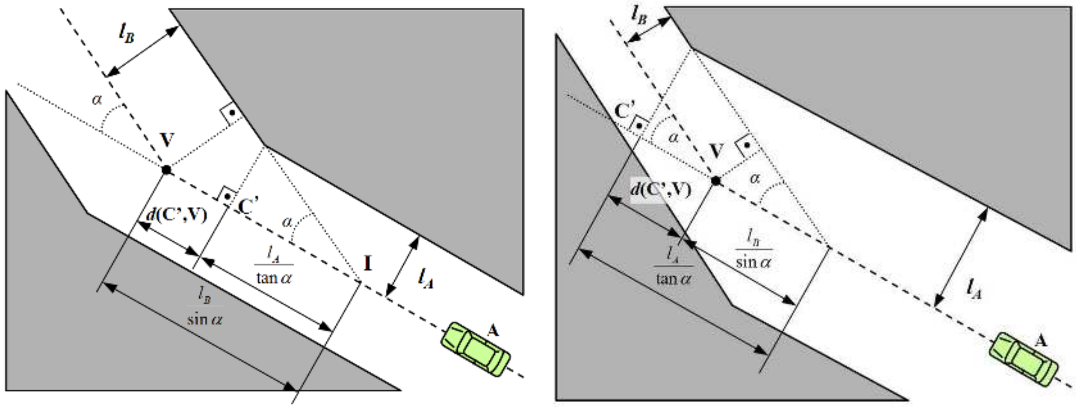
The three terms on the right hand of the equality can be computed using the known values. Point C' depends on l_A, l_B, α and the vertex coordinates (V) which the two streets have in common. Figure 8 graphically depicts the mathematical factors used in computations, and the two different possible scenarios where point C' can be located (a) nearer or (b) further to the vertex V than vehicle A. Hence, the value of $d(A, C')$ can be calculated as follows:

$$d(A,C') = \begin{cases} d(A,V) - d(C',V) & \text{if} \quad \frac{l_B}{\sin\alpha} \geq \frac{l_A}{\tan\alpha} \\ d(A,V) + d(C',V) & \text{if} \quad \frac{l_B}{\sin\alpha} < \frac{l_A}{\tan\alpha} \end{cases} \tag{8}$$

Where $d(C', V)$ is computed as follows:

$$d(C',V) = \left| \frac{l_B}{\sin\alpha} - \frac{l_A}{\tan\alpha} \right| \tag{9}$$

Distance between points B and C is equal to the minimum distance (d_{min}) between point B (x_B, y_B) and the line r (formed as an extension of the street where A is located, see Figure 7) in the form $A_r \cdot x + B_r \cdot y + C_r = 0$. This distance can be computed using the following expression, corresponding to the minimum geometrical distance between a point and a straight line:



(a) (b)

Fig. 8. Graphical explanation of the computation of $d(C', V)$, (a) when $d(A, C') < d(A, V)$, and (b) when $d(A, C') > d(A, V)$.

$$d(B, C) = d_{min}(B, r) = \frac{|A_r \cdot x_B + B_r \cdot y_B + C_r|}{\sqrt{A_r^2 + B_r^2}} \tag{10}$$

Finally, $d(A, C)$ has the following value:

$$d(A, C) = d(A, V) + d(V, C) = d(A, V) + \frac{d(B, C)}{\tan \alpha} \tag{11}$$

All the previous calculations are only valid if the vehicles are located in adjacent streets with a common junction. However, if there is a series of streets forming a path between the vehicles, this scheme can be extended to allow propagation through several streets. First of all, we need to find the intersections between the segment joining both vehicles and the segments representing the streets in the path between them using Equation 5. The visibility test must be passed at every pair of points which belong to adjacent streets until the receiver vehicle is reached. If the visibility scheme fails for some pair of points, or there is no intersection in a street with the segment between the vehicles, then the two vehicles are not considered to be in line-of-sight. This process is illustrated on Figure 9, where vehicles A and B are not moving on adjacent streets and an additional point (P_1) is needed in the separating street to determine if communication is possible, i. e., there must be line-of-sight between vehicle A's position and P_1, and between P_1 and B's position.

Note that the proposed visibility scheme only determines if there are obstacles (i.e. buildings which could block signal propagation) between the sender and receiver. Success in communication also depends on the distance between them, and on the attenuation scheme used (for example, our proposed attenuation scheme).

3) Vehicles near junctions: The electromagnetic waves forming the wireless signal can experience the effects of reflection, refraction and diffraction due to the presence of solid obstacles in urban scenarios, like buildings. Hence, some situation where vehicles are not in line-of-sight can result in effective communication between them.

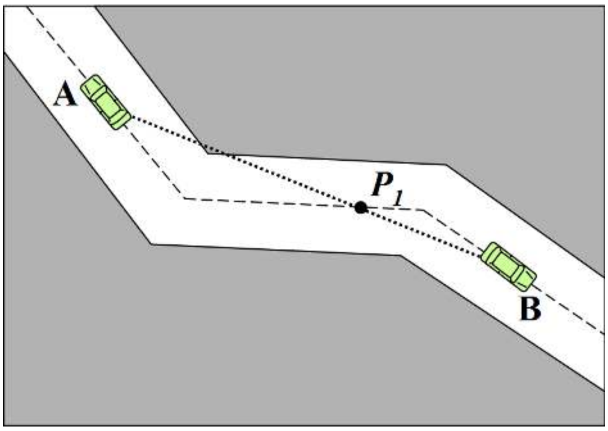


Fig. 9. Extension of the calculations to allow multi-street propagation.

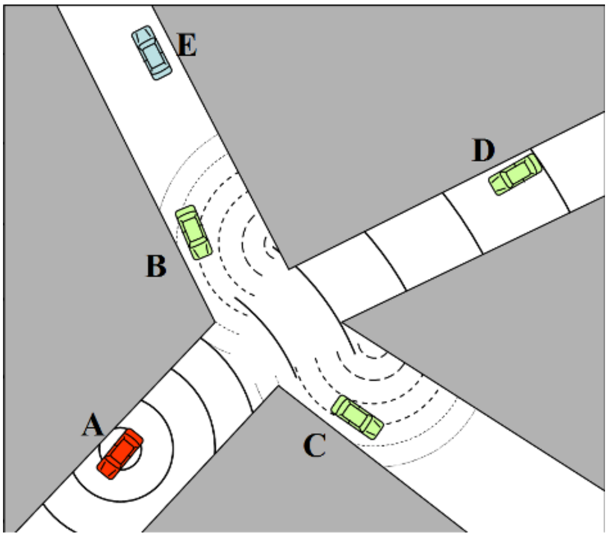


Fig. 10. Vehicles in non-line-of-sight are able to receive the message through reflection and diffraction if they are close enough to a junction.

Our empirical results showed that only vehicles close to junctions are able to receive enough power to obtain the messages in non-line-of-sight conditions, similarly to the results obtained in [4], [5]. Vehicles located more than 20 meters away from the junction were not able to successfully receive warning messages. This situation is considered in our visibility model by including the possibility to receive a message if a vehicle is located close enough (less than 20 meters) to a junction.

Figure 10 shows an example of this effect. Vehicle A is transmitting a warning message. Vehicle D is able to receive it since it is in line-of-sight, but vehicles B, C and E cannot communicate directly. However, vehicles B and C are able to receive it thanks to the reflections of the signal on the nearby buildings, while vehicle E is too far from the junction to receive enough signal power.

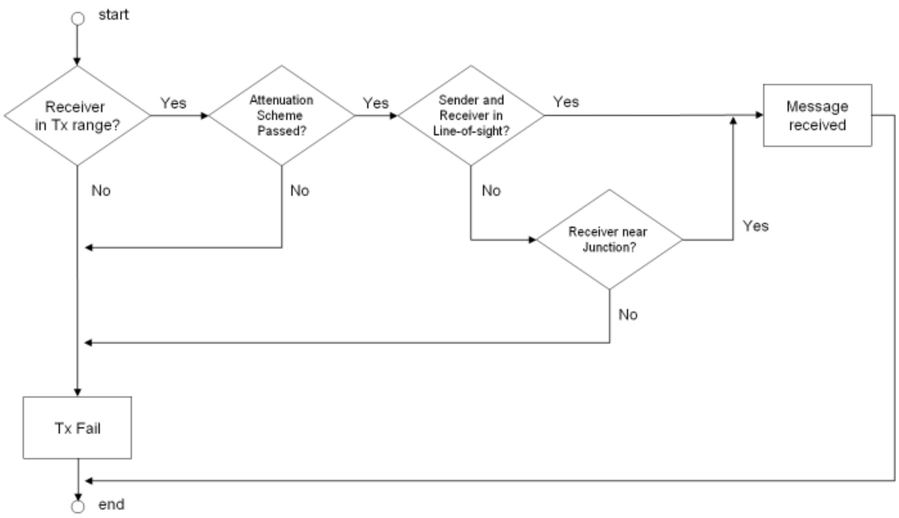


Fig. 11. Proposed model flowchart.

C. *Summary of operation of our Topology-based Visibility approach*

Figure 11 shows a flowchart with the conditions used to determine if a packet is successfully received using our proposed model. The computational time required to determine the set of vehicles in line-of-sight of another vehicle is considerably high compared to the time needed to apply the attenuation test. Thus, we first use the attenuation scheme over a vehicle and its neighbors to determine the vehicles which could potentially receive the message. The visibility scheme is applied afterwards in two steps to generate the final receiving set. The first step determines if there is line-of-sight between sender and receiver. If this check fails, an additional test to account for reflection and diffraction (i.e., receiver is near enough to a junction) is performed. For a packet to be correctly received, both attenuation and visibility tests must be successfully passed.

IV. Simulation Environment

In this section, we present our simulation environment. Simulations were done using the ns-2 simulator, modified to include the IEEE 802.11p standard closely. In terms of the physical layer, the data rate used for packet broadcasting is 6 Mbit/s, as this is the maximum rate for broadcasting in 802.11p. The MAC layer was also extended to include four different priorities for channel access. Therefore, application messages are categorized into four different *Access Categories* (ACs), where AC0 has the lowest and AC3 the highest priority.

The purpose of the 802.11p standard is to provide the minimum set of specifications required to ensure interoperability between wireless devices attempting to communicate in potentially rapid changing communication environments. For our simulations, we chose the IEEE 802.11p because it is expected to be widely adopted by the industry. For 802.11p-based VANETs, the received signal strength will largely depend on the presence of obstacles and the distance from the sender.

Each simulation run lasted for 450 seconds. In order to achieve a stable state, we collect data only after the first 60 seconds. We tested our model by evaluating the performance of a Warning Message Dissemination mechanism where each vehicle periodically broadcasts information about itself or about an abnormal situation (icy roads, traffic jam, etc.).

In order to mitigate the broadcast storm problem, our simulations use the *Street Broadcast Reduction* (SBR) scheme [15], which outperforms the flooding, the distance-based, and the location-based schemes presented in [16], and it can overcome corners and road intersections by allowing data propagation on different roads. The SBR scheme only allows forwarding messages when the distance between sender and receiver is greater than a threshold, or in situations where the receiver is the closest vehicle to a junction and rebroadcasting could make the message reach new streets.

With regard to data traffic, vehicles operate in two modes: (a) warning mode, and (b) normal mode. Warning-mode vehicles inform other vehicles about their status by sending warning messages periodically (every T_w seconds). These messages have the highest priority at the MAC layer. Normal-mode vehicles enable the diffusion of these warning packets and, periodically (every T_b seconds), they also send $beacons$ with information such as their positions, speed, etc. These periodic messages have lower priority than warning messages and are not propagated by other vehicles. With respect to warning messages, each vehicle is only allowed to propagate once for each sequence number, i.e., older messages are dropped.

For realistic simulations, it is specially important that the chosen mobility generator offers a detailed microscopic traffic simulation and the capability to import network topologies from real maps. Our mobility simulations are performed with SUMO [17], an open source traffic simulation package which has interesting microscopic traffic capabilities such as: (a) collision-free vehicle movement, (b) multi-lane streets with lane changing, (c) junction-based right-of-way rules, and (d) traffic lights emulation. SUMO can also import maps directly from map databases such as OpenStreetMap [18] and TIGER [19].

Our mobility simulations account for areas with different vehicle densities. In a realistic town setting, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [12] to add points of attraction in roadmaps. To generate the movements for the simulated vehicles, we used the Krauss mobility model [20] (with some modifications to allow multi-lane behavior [21]) found in SUMO. The Krauss model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)}{\tau(t) + 1} + \eta(t), \tag{12}$$

where v represents the speed of the vehicle, v_1 is the speed of the leading vehicle, g is the gap to the leading vehicle, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random variable with a value between 0 and 1.

Finally, concerning the simulated scenario, we have selected three different real cities representing different environments (see Figure 12). The city of Manhattan (KS, USA) has a very regular street layout where simulations would have a very similar behavior compared to simulations using synthetic Manhattan-grid layouts. The city of Teruel (Spain) is an example of a town with a low density of streets and junctions, arranged in a complex layout different from typical Manhattan-grid layouts. The city of Valencia (Spain) represents a city

TABLE I

PARAMETER VALUES FOR THE SIMULATIONS

Parameter	**Value**
number of vehicles	$50, 100, 200, 300, 400$
maximum speed	$23\ m/sec. \approx\ 83\ km/h$
simulated area	$2000m \times 2000m$
number of warning mode vehicles	3
warning packet size	$256B$
normal packet size	$512B$
packets sent by vehicles	$1\ per\ second$
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
maximum transmission range	$400m$
SBR distance threshold (D) [15]	$200m$
Visibility th_s	$20m$
mobility generator	SUMO [17]
mobility model	Krauss model

TABLE II

MAIN TOPOLOGICAL FEATURES OF THE SELECTED MAPS

Selected city map	Manhattan (KS, USA)	Teruel (Spain)	Valencia (Spain)
Streets/km^2	81	148.25	640.25
Junctions/km^2	27.5	108	276.5
Avg. street length	$216.34m$	$78.99m$	$33.36m$
Avg. lanes/street	1.25	1.14	1.06

with an extremely high density of streets and junctions. The specific features of these scenarios are shown in Table II. We can observe that the three scenarios present very different values, especially in terms of street density and average street length, with the map of Manhattan representing the simplest layout with few long streets, and the opposite situation with the city of Valencia. These factors might be decisive to determine the effectiveness of warning message dissemination.

The size of all scenarios is 4 km^2, but the number of vehicles involved in each simulation takes different values: 50 (12.5 vehicles/km^2), 100 (25 vehicles/km^2), 200 (50 vehicles/km^2), 300 (75 vehicles/km^2) and 400 (100 vehicles/km^2). Table I shows the representative parameter values used in our simulations.

V. SIMULATION RESULTS

In this section, we study the performance of information dissemination in VANETs when different topologies are used as simulation scenarios. The objective of this evaluation consists on finding which factors of the dissemination process become affected when a more realistic simulation environment is used. The results will help reveal further the importance of realistic simulation in VANETs.

(a) (b) (c) (d) (e) (f)

Fig. 12. Scenarios used in our simulations: (a) Fragment of the city of Manhattan (KS) obtained from OpenStreetMap, (b) the same fragment as a street graph in SUMO, (c) fragment of the city of Teruel (Spain) obtained from OpenStreetMap, (d) the same fragment as a street graph in SUMO, (e) fragment of the city of Valencia (Spain) obtained from OpenStreetMap, and (f) the same fragment as a street graph in SUMO.

Warning Message Dissemination of utmost importance in VANETs since rescue time is a critical factor when dealing with accident notification and assistance. An accurate simulation of warning dissemination using realistic parameters is necessary to ensure the proposed system presents an adequate behavior in a real-life environment and not only in theory. The difference between a performance evaluation using realistic and unrealistic settings may result in a cost of human lives which is not affordable and thus all novel schemes should be validated in realistic conditions.

We selected two metrics that help us to evaluate the performance of warning dissemination in a VANET: warning notification time and number of packets received per vehicle. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning-mode vehicle and it is critical when dealing with the usefulness of the system (a warning message delivered too late is useless when facing dangerous situations). The number of packets received per vehicle (including beacons and warning messages) provides an indication of the level of channel contention and the possibility of producing broadcast storms. These metrics are evaluated and compared in different scenarios using existing schemes and our proposed scheme. The differences will state if simpler models are enough for VANET simulations. All results represent an average of over 30 executions with different scenarios (maximum error of 10% with a degree of confidence of 90%).

A. Impact of using realistic topologies in VANET simulation

First of all, we will study the effect of using different topologies constraining vehicles' movements on warning message dissemination performance. The simplest models do not consider obstacles at all, or they arrange buildings interfering wireless signal in regular Manhattan-grid layouts. The objective is determining if these simple approaches are enough to obtain useful results.

In order to better observe the effects of using different visibility schemes, Figure 13 shows the results obtained under three different scenarios: (i) an obstacle-free environment (ns-2 current visibility scheme), (ii) the visibility scheme presented in Section II-B for synthetic Manhattan scenarios, and (iii) the proposed visibility scheme for realistic roadmaps, using the map taken from the city of Valencia where the streets are arranged irregularly. We use a network density of 50 vehicles/km^2 (200 vehicles in 4 km^2) to compare these configurations.

If we do not account for obstacles, warning messages rapidly reach 100% (which is unrealistic). As expected, there are more blind vehicles using a realistic topology than using a synthetic Manhattan layout, but the warning notification time is lower (60% of vehicles are informed in only 0.3 seconds), as the propagation process needs less time to be completed (0.6 seconds). The higher percentage of blind vehicles in a real scenario is due to the complex street topology used (which makes it harder to reach specific areas in the map), while in the Manhattan layout, streets are straight and signal reaches longer distances (making it easier to discover new vehicles). However, using real maps, there are many more junctions, which increases the probability of a vehicle to be near a junction and in all the adjacent streets (which, in contrast to Manhattan layouts, its number can be greater than four). This effect reduces the warning notification time.

Table III shows a summary of the average performance results obtained when simulating different visibility schemes. The data presented for the warning notification time is the time required to inform at least 60% of

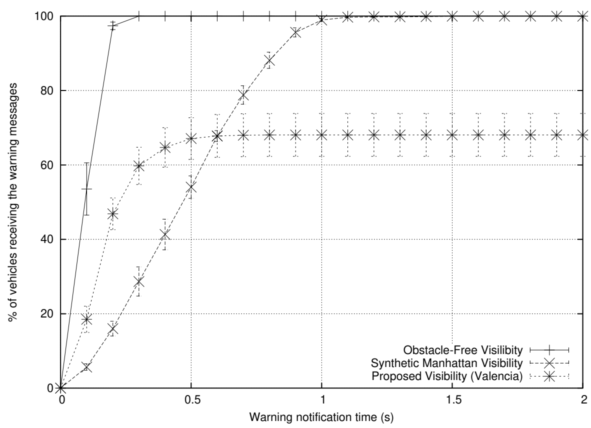


Fig. 13. Comparisons of warning notification time when using the realistic attenuation scheme and varying the visibility/layout schemes.

TABLE III

AVERAGE PERFORMANCE UNDER DIFFERENT VISIBILITY SCHEMES

Performance metric	Schemes		
	Obstacle-Free	**Synthetic Manhattan**	**Our Proposal**
Warning notification time (s)	0.13	0.55	0.3
% of blind vehicles detected	0	0.03	31.93
Number of packets received	5489.07	1131.53	757.63

the vehicles in the simulation. As shown, when accounting for the effect of buildings in signal propagation, the system requires more time to warn the rest of the vehicles, although warning notification time is lower in our visibility scheme. Nevertheless, when simulating real map layouts, the percentage of blind vehicles slightly increases, and the number of packets received per vehicle is drastically reduced.

All the obtained results show that there are enough differences between unrealistic topologies and realistic ones to consider the previous results little representative, since it is not probable to obtain similar performance under real-life conditions. Therefore, we will make an extensive use of realistic topologies in our simulations.

B. Performance Evaluation of Information Dissemination in Realistic Topologies

We will now test the impact of different realistic simulation scenarios and different vehicle densities on the effectiveness of the warning message dissemination.We vary the network density from 12.5 vehicles/km^2 to 100 vehicles/km^2 and we use the realistic maps shown in Figure 12. These maps present noticeable differences in terms of street layout, average street length and street density, to represent different environments that could be found in real cities.

1) Warning notification time: Figure 14 shows how the propagation process develops in the city of Manhattan, which contains long and nearly orthogonal streets. This regular layout allows signal to propagate more easily through the straight streets, thus achieving a high percentage of receiving nodes for all vehicle densities. For densities above 50 vehicles/km^2, at least 80% of the vehicles are informed about the dangerous situation and more than 50% of the vehicles receive the warning message in less than 0.2 seconds. In addition, the differences in efficiency of the dissemination process are less noticeable as vehicle density increases. The propagation process is the longest of all scenarios, as it needs 0.8 seconds to reach a stable state where no more vehicles are informed.

In Figure 15, the simulation scenario used is the city map of Teruel, a scenario arranged in an irregular layout with low street density. As shown, increasing vehicle density increases the number of vehicle receiving the warning message. In all cases, the propagation process was completed in less than 0.5 seconds. However, with higher density this process is faster (only 0.2 seconds to inform 60% of the vehicles). With a small vehicle density (12.5 nodes/km^2), around 25% of the rest of the vehicles are informed of the dangerous situation, which indicates that only the closest vehicles receive the warning messages. It is noted that the percentage of vehicles receiving warning messages is similar for all simulations beyond 25 vehicles/km^2; in fact, simulating 300 vehicles achieves better average results than simulating 400 vehicles. This effect arises when the maximum propagation capacity of the scenario is reached, and it allows us to identify the presence of some broadcast storm problem when the vehicle density exceeds 75 vehicles/km^2.

Finally, Figure 16 represents the results attained using the city of Valencia map layout, formed by very short and irregularly arranged streets. This layout has more streets than the previous one, which reduces the probability of having many vehicles in the same street, thus reducing the broadcast storm problem. The results are similar to those attained in the map of Manhattan, although with a slightly lower percentage of informed vehicles in all configurations. However, for densities above 50 vehicles/km^2 the differences become smaller. As shown, with 100 vehicles, warning messages reach 60% of the vehicles, and this percentage increases up to 90% with 300 and 400 vehicles. The propagation process now needs around 0.6 seconds to complete, thus being intermediate between the results obtained using the maps of Manhattan and Teruel.

We can deduce from these results that the selected road topology has a great impact on warning message dissemination efficacy. Scenarios with long streets arranged in a Manhattan way allows warning messages to disseminate efficiently, increasing the percentage of informed nodes. Nevertheless, if the street map is formed by short streets in an irregular layout, the propagation process will develop slowly even if the vehicle density is high.

To better analyze the effect of city streets layout on warning notification time, we present the previous results according to the density of streets. Figure 17 shows the warning notification times obtained when simulating with the same vehicle density but varying the city scenario. When using 50 vehicles, the street layout has no serious effect on both the number of informed vehicles and the time required to complete the warning dissemination. With low densities, our scheme is able to inform at least 30% of the vehicles in all cases. As we increase the vehicle density, the differences are more noticeable. With 100 vehicles, the average number of vehicles receiving the warning message varies within a 20% interval, with worst results achieved using the city map of Teruel and the best results with the city map of Manhattan. Using 200 nodes, we get a situation where the different confidence intervals are not overlapped, proving that the performance of our dissemination scheme is really dependent on the selected city map layout. When vehicle density is at 300, the percentage of vehicles receiving the warning message is quite similar for both cities (i.e., Teruel and Valencia). However, for

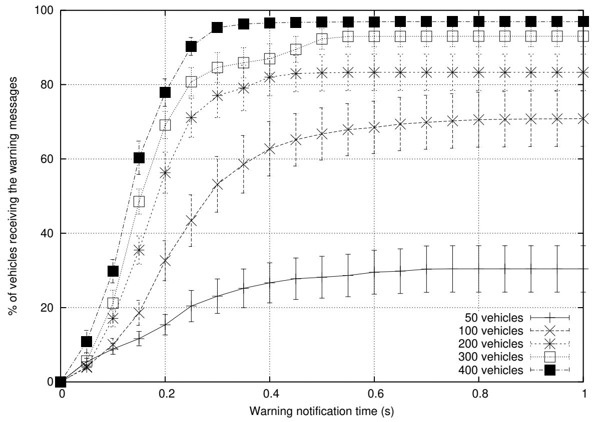


Fig. 14. Warning notification time when varying the vehicle density in the city of Manhattan.

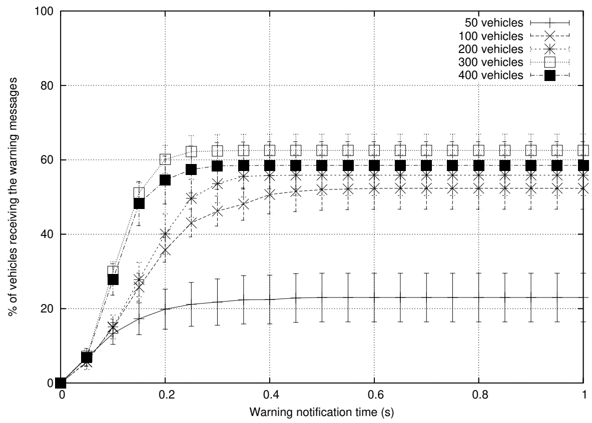


Fig. 15. Warning notification time when varying the vehicle density in the city of Teruel.

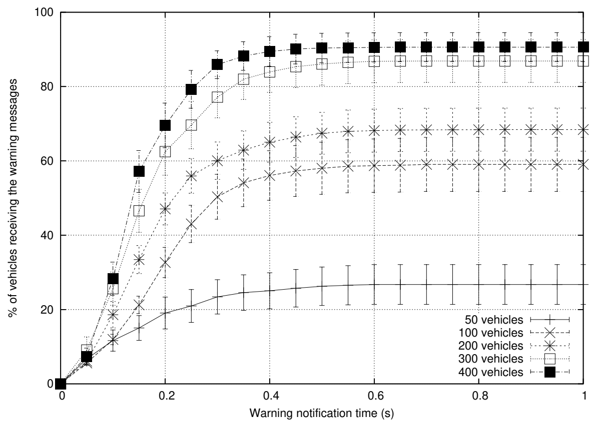
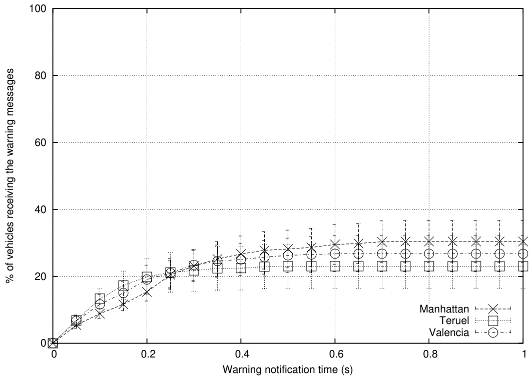
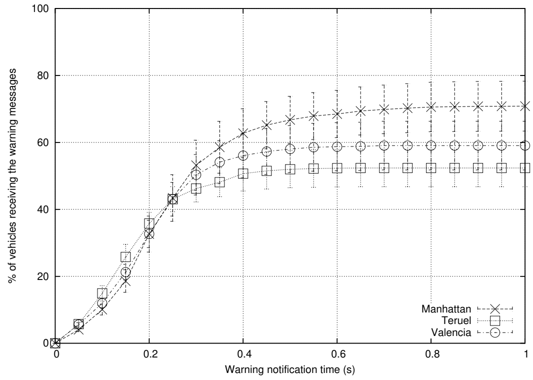


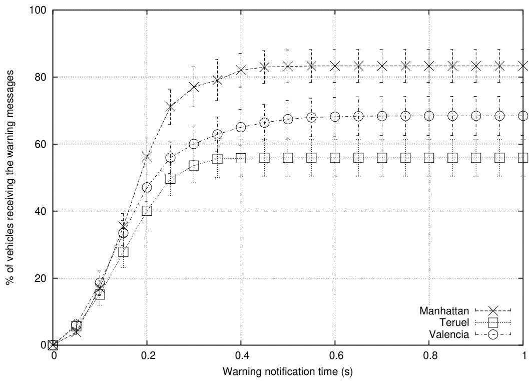
Fig. 16. Warning notification time when varying the vehicle density in the city of Valencia.



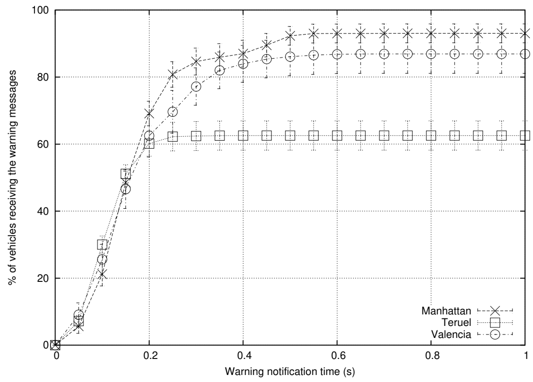
(a)



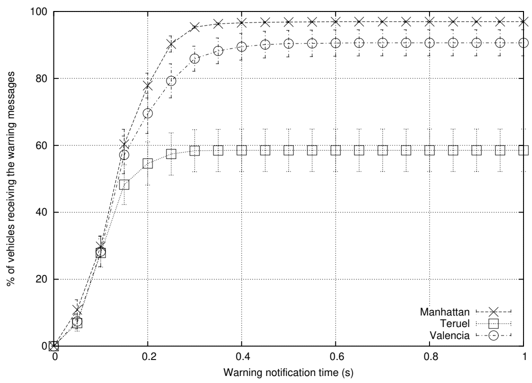
(b)



(c)



(d)



(e)

Fig. 17. Warning notification time when varying the simulation scenario using (a) 50 vehicles, (b) 100 vehicles, (c) 200 vehicles, (d) 300 vehicles, and (e) 400 vehicles.

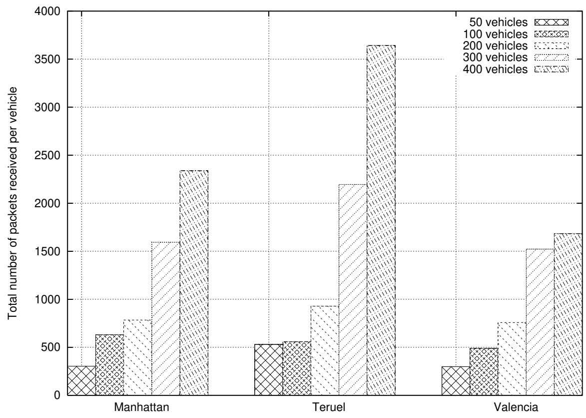


Fig. 18. Average number of packets received per vehicle with different cities, road topologies, and vehicle densities.

the city of Manhattan, only about 60% of total vehicles are warned. Similar behavior is observed when vehicle density is increased to 400.

In summary, increasing vehicle density increases the percentage of vehicles warned (more so for the cities of Teruel and Valencia) and reduces the warning notification time (for all 3 cities).

2) Received packets: We now focus on information dissemination performance based on the average number of packets received per vehicle when varying the vehicle density (Figure 18).

As shown, when the number of vehicles is 200 or below, the simulations using the three different cities have a similar behavior. This means that, in a sparsely connected vehicle network, warning message dissemination works with a noticeable performance in terms of informed vehicles and packets received per vehicle.

However, with increasing vehicle density, the average number of received packets generally increases. In a city environment with reduced street density and short streets (like the city of Teruel), excessive channel contention exists with 300 and 400 vehicles (75 and 100 vehicles/km^2, respectively). In Valencia, this problem is not so noticeable due to the higher number of streets, which impedes the signal from reaching as many vehicles, and thus reducing the probability of having two vehicles in line-of-sight. In fact, when using the map of Valencia, the number of received packets per vehicle is almost the same with 300 and 400 vehicles. Finally, with a Manhattan scenario, we get similar results for 300 nodes when compared to the map of Valencia, although increasing vehicle density to 100 vehicles/km^2 (400 nodes) greatly increases the number of packets received.

VI. Overall Evaluation Summary

In the previous section, we evaluated the performance of information dissemination in terms of warning notification time and average number of messages received per vehicle when different urban topologies are used as simulation scenarios.

Figures 14, 15 and 16 show the warning notification times with varying vehicle densities. These figures show that with increasing vehicle density, more vehicles can be warned at a given time. Also, at a given percentage of vehicles receiving the warning message (say 20%), it takes less notification time as vehicle density increases. Figure 17 provides further insight into the impact of different city road topologies on information dissemination performance. Clearly, the Manhattan city map yields the highest possible warning coverage across all vehicle densities. This is followed by Valencia and finally Teruel. Figure 18 shows that Teruel yields the highest channel contention at high vehicle density. This is due to the combination of short average street length and low street density, which highly increase the probability of finding numerous vehicles located in the same street or near junctions.

To sum up, the warning message propagation process will be noticeably affected by the urban topology where the dissemination takes place. The most critical factors to be considered are the street density and the average street length in the topology surrounding the sender vehicle. When the roadmap is formed by a few long streets, like synthetic Manhattan-style grids, the dissemination will work efficiently even in low vehicle density scenarios. However, if the average street length is too low, broadcast storms are prone to occur, with more probability as vehicle density increases. Finally, the number of messages received per vehicle is noticeable reduced in scenarios with high street density, and thus the dissemination process develops efficiently without yielding broadcast storms.

VII. CONCLUSIONS

Many existing research works in VANETs do not consider the effects of buildings, road topologies, and the simulation models used are overly simplistic. In this paper, we introduced the Topology-based Visibility scheme which takes into account realistic road topologies and packet error rate (PER) characteristics.

Our simulation results show that vehicle density and city streets layout are important factors that affect the performance of warning message dissemination in VANETs. As vehicle density increases, warning notification time decreases in all city scenarios. City maps (and hence road topologies) have little effect on warning notification time and number of received packets in scenarios with low vehicle density, but they affect warning message dissemination performance at high vehicle density scenarios. Simulations results also revealed that the Manhattan topology (i.e., the map with the longest streets) yields the highest warning coverage across all vehicle densities. Thus, results obtained under such topologies are optimistic, and not applicable to cities with different topologies.

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Francisco J. Martinez is an associate professor in the Department of Computers and Systems Engineering at the University of Zaragoza in Spain. He graduated in Computer Science and Documentation at the Technical University of Valencia in 1996 and 1999, respectively. He received his Ph.D. degree in Computer Engineering from the Technical University of Valencia in 2010. His current research interests include VANET simulation, intelligent transportation systems, traffic safety, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. He is member of the IEEE.

Manuel Fogue earned BSc and MSc degrees from both the University of Zaragoza in 2007 and the University Jaume I of Castellon in 2009, respectively. In both cases, he graduated with honors. He is a PhD candidate in the Computer Networks research group (GRC). His research interests include VANET simulation, intelligent transportation systems, traffic safety, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

C-K Toh received his PhD in Computer Science from Cambridge University (1996) and earlier EE degrees from Manchester University (1991) and Singapore Polytechnic (1986). He was a visiting professor at YALE (USA), Fudan (China), KTH (Sweden), KNU (Korea), NCKU (Taiwan), and Osaka University (Japan). From 2004-2009, he was an Honorary Full Professor at the University of Hong Kong. Previously, he was a tenured Chair Professor at the University of London and the Director of Research at TRW Tactical Systems Inc., USA. Earlier on, he led the DARPA Deployable Ad Hoc Networks program at Hughes Research Labs, USA. Dr. Toh has two sole-authored books: (a) "Ad Hoc Mobile Wireless Networks" (Prentice Hall, ISBN 0130078174, 2001), and (b) "Wireless ATM" (Kluwer, ISBN 079239822X, 1997). He has consulted for various companies, including KDDI (Japan), Hughes (USA), and Mitsubishi (USA). Dr. Toh is a Fellow of the British Computer Society (BCS), New Zealand Computer Society (NZCS), Hong Kong Institution of Engineers (HKIE), and Institution of Electrical Engineers (IEE). He is a recipient of the 2005 IEEE Institution Kiyo Tomiyasu Medal (for pioneering contributions to communication protocols in ad hoc mobile networks) and the 2009 IET Ambrose Fleming Medal (for achievements in communications engineering). In 2009, he was named an IEEE Fellow and AAAS Fellow.

Juan-Carlos Cano is a full professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He earned an MSc and a Ph.D.in computer science from the UPV in 1994 and 2002 respectively. From 1995 to 1997 he worked as a programming analyst at IBM's manufacturing division in Valencia. His current research interests include power aware routing protocols and quality of service for mobile ad hoc networks and pervasive computing.

Carlos T. Calafate is an associate professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He graduated with honors in Electrical and Computer Engineering at the University of Oporto (Portugal) in 2001. He received his Ph.D. degree in Computer Engineering from the Technical University of Valencia in 2006, where he has worked as an assistant professor since 2005. He is a member of the Computer Networks research group (GRC). His research interests include mobile and pervasive computing, security and QoS on wireless networks, as well as video coding and streaming.

Pietro Manzoni is a full professor in the Department of Computer Engineering at the Polytechnic University of Valencia (UPV) in Spain. He received the MS degree in computer science from the "Universitá degli Studi" of Milan, Italy, in 1989, and the PhD degree in computer science from the Polytechnic University of Milan, Italy, in 1995. He is an associate professor of computer science at the Polytechnic University of Valencia, Spain. His research activity is related to wireless networks protocol design, modelling, and implementation. He is member of the IEEE.